Impact of Data Assimilation and Resolution on Modeling the Gulf Stream Pathway

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Abstract

In this paper, we study, in detail, one important aspect of our ongoing work on global ocean prediction. Modeling the behavior of western boundary currents, like the Gulf Stream, has been a long-standing issue. Recent modeling results suggest that the abyssal currents play an important role in determining the pathway of the Gulf Stream. The present-generation ocean prediction model fails to adequately reproduce the Gulf Stream pathway, and does not generate a vigorous abyssal circulation. Here we use twin simulations, at different horizontal resolutions and with and without data assimilation, to study their effects on modeling the observed Gulf Stream pathway. Increasing the resolution of the model improves the strength of the abyssal circulation, but still fails to predict the Gulf Stream pathway. Surprisingly, assimilating sea level anomalies and upper ocean profiles produces a robust abyssal circulation and a Gulf Stream pathway similar to the observed pathway. However, the Gulf Stream with assimilation is weaker than observed and, unlike most regions of the deep ocean; there is no skill in the 14-day forecasts. All simulations were performed under our current Department of Defense (DoD) High Performance Computing Modernization Program (HPCMP) Challenge Project, Eddy Resolving Global Data Assimilation Including Tides, or our earlier HPC Challenge Project, Global Ocean Prediction using HYCOM.

1. Introduction

Modeling the behavior of western boundary currents in ocean general circulation models has been a long-standing challenge. For the Gulf Stream (GS), the western boundary current of the North Atlantic Ocean, the inability of the models to get the GS to separate from the continental shelf at Cape Hatteras and to extend eastward as a meandering jet remains a problem (Hurlburt, et al., 2010). Recently, Hurlburt and Hogan, (2008) propose that a realistic Gulf Stream pathway requires: 1) a sufficiently inertial Gulf Stream, and 2) steering by abyssal currents. The abyssal currents could be generated by either the Deep Western Boundary Current (DWBC) associated with the Meridional Overturning Circulation (MOC) or by topographic coupling of the eddy-driven circulation.

We test this hypothesis by comparing the results from a series of twin experiments using US Naval Research Laboratory (NRL) global Hybrid Coordinate Ocean Model (HYCOM), compared to satellite estimates of the Gulf Stream pathway and its variability. To determine the actual pathway of the Gulf Stream we use the daily frontal analyses from the Naval Oceanographic Office to locate the GS north wall. The 12-year mean frontal location and 1σ variability are plotted as white lines over the satellite altimeter sea-surface height (SSH) variability. Using a Gaussian jet model, the 16-year mean location of the GS and 1σ variability are plotted as black lines. The path of the GS is well-defined by the SSH variability with the 1σ spread increasing from Cape Hatteras to the New England Seamount Chain (NESC), and nearly constant from there to the Newfoundland Rise (NFR). The north-wall from the SST frontal analyses lies approximately 20 km north of the core of the mean GS jet until the NFR is reached, where the GS bifurcates into the North Atlantic Current and the Azores Current.

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2. Simulating the Gulf Stream in a Global Ocean General Circulation Model

The base simulation for the twin experiments is interannually forced by winds and buoyancy fluxes from the Navy Operational Global Atmospheric Prediction System (NOGAPS) with the boundary layer winds increased by a regression correction from QuikSCAT scatterometer winds, proposed by Kara et al., (2009). The GS core-speed in layer 6 (~25m) near the separation point at Cape Hatteras is 1.4 m s^{-1}, which is weaker than the observed range of 1.6 to 2.1 m s^{-1}. The core speed remains greater than 1 m s^{-1} to 70°W and decreases rapidly east of 70°W (Figure 2). The model GS pathway is south of the observed pathway. A strong recirculation gyre is observed to the south of the GS. The key abyssal current at 72°W, described by Hurlburt and Hogan, (2008), is observed with a speed greater than 8 cm s^{-1}, but the other key abyssal current at 68°W doesn't exist. The MOC is very shallow and relatively weak with a transport less than 16 Sv. The SSH variability shows the strong southern recirculation gyre with much of the variability south of the observed GS pathway and little eddy-activity east of 60°W, compared to the observed SSH variability shown in Figure 1.

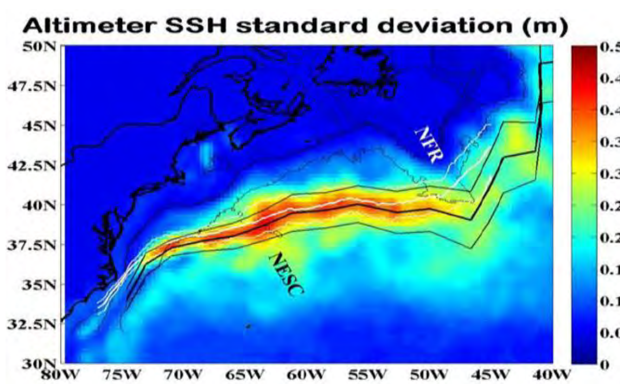

Figure 1. The mean path of the Gulf Stream and 1 extents from AVHRR SST (light white lines) and altimeter SSH (black lines) on top of the SSH standard deviation

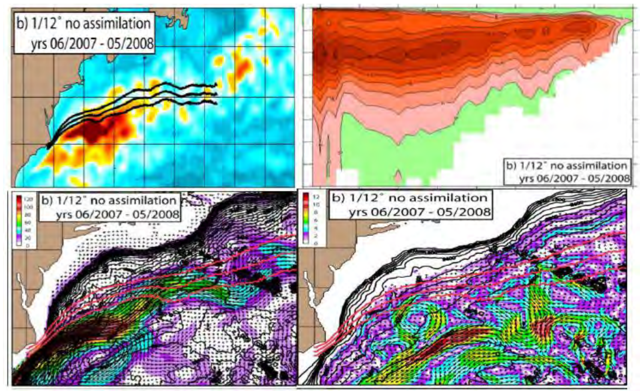

Figure 2. The NOGAPS with QuikSCAT correction inter-annually forced simulation with layer 6 (~25m) velocity in upper-left panel and the layer 27–29 (~3,500–4,500 m) velocity in the upper-right panel with the mean GS pathway shown in red. The SSH standard deviation and the MOC are shown in the lower-left and right panels, respectively.

3. Impact of Model Resolution

In their idealized study, Hurlburt and Hogan, (2008) noted that increasing the resolution of the model increased the strength of the eddy driven abyssal circulation to provide the deep steering currents, even in the absence of a DWBC. To investigate the impact of resolution, we perform a set of twin experiments forced by the ERA-40 climatology, with a QuikSCAT wind speed correction at nominal 7 km (1/12°, Figure 3) and 3.5 km (1/25°, Figure 4) resolution. In the upper-left hand panels, the 4-year mean sea surface and the GS north wall pathway are shown. In the 1/12° HYCOM, the mean path shows premature separation from the coast with high-SSH variability south of the mean GS path partly associated with excessive meander variability south of Cape Hatteras which is found in both the 1/12° and 1/25° simulations. The separation velocity of the 1/12° simulation at 1.48 m s^{-1} is weaker than the observed range of 1.6 to 2.1 m s^{-1}. In snapshots (not shown), the Gulf Stream occasionally overshoots and hugs the continental shelf in the 1/12° HYCOM simulation. The MOC is relatively weak at just over 16 Sv for both simulations, and more importantly, the deep limb of the MOC is very shallow, consistent with too much Labrador Sea Water and not enough Denmark Straits Overflow Water. The corresponding abyssal circulation is weak in the 1/12° simulation. The key abyssal current at 72°W is weak at less than 4 cm s^{-1} and the key abyssal current at 68.5°W is absent. In the 1/25° HYCOM simulation, the Gulf Stream performance is improved with a more realistic mean sea surface and pathway and a stronger abyssal circulation with both key abyssal currents present. The separation velocity of 1.55 m s^{-1} is at the low end of the observed range. The SSH variability still shows excessive meandering upstream of Cape Hatteras, and premature separation at times.

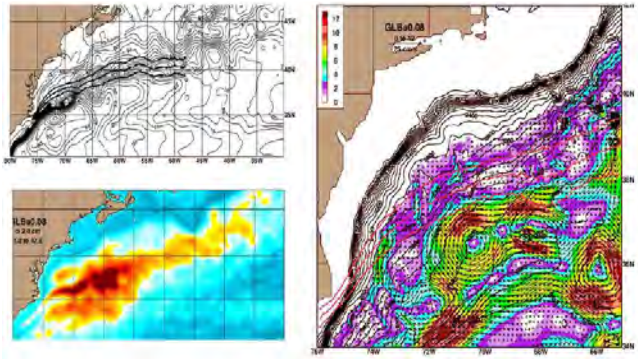

Figure 3. Climatologically-forced 1/12° simulation with the mean SSH and mean observed GS pathway in upper-left and SSH standard deviation in lower-left and layer 27–29 (~3,500–4,500 m) currents in right panel

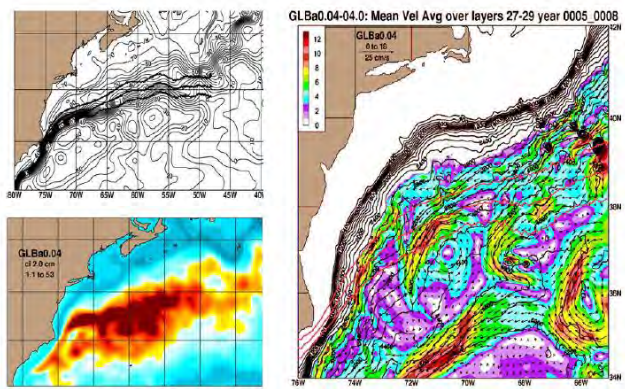

Figure 4. Climatologically-forced 1/25° simulation with the mean SSH and mean observed GS pathway in upper-left and SSH standard deviation in lower-left and layer 27–29 (~3,500–4,500 m) currents in right panel

4. Impact of Data Assimilation

Increasing the resolution of the model improved the behavior of the Gulf Stream, but serious mean pathway errors remain, and instantaneous pathways differ significantly. Data assimilation is used to correct the model to resemble the observations. To investigate the impact of data assimilation, two sets of twin experiments are presented with one set of experiments characterized by weak winds (NOGAPS without QuikSCAT correction), and assimilation of SSH anomalies using the technique of Cooper and Haines, (1996); and the second set of experiments using stronger winds (NOGAPS with QuikSCAT correction), and assimilation of SSH anomalies using synthetic temperature and salinity profiles from the Modular Ocean Data Analysis System (MODAS) described by Barron et al., (2007). All of the following figures (Figures 5–9) have the same structure. In panels (a) and (c) the results from a simulation forced by winds without a QuikSCAT correction and a hindcast with Cooper-Haines, (1996) assimilation of SSH anomalies, and in panels (b) and (d) the results from a simulation forced by winds with a QuikSCAT correction and a hindcast with MODAS synthetic profile assimilation of SSH (Barron et al., 2007).

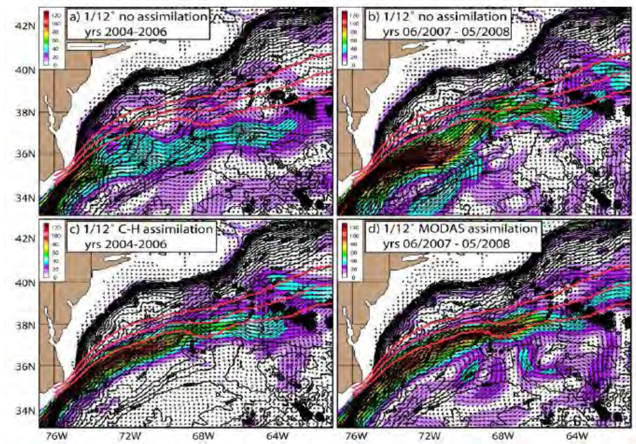

Figure 5. Mean velocities in layer 6 (~25 m) with the mean Gulf Stream pathway ± 1σ overlaid in red and the bathymetry contoured at 200 m intervals from four 1/12° global HYCOM simulations: a) inter-annually forced weak Gulf Stream with separation velocity of 1.1 m s^{-1}; b) inter-annually forced stronger Gulf Stream with separation velocity of 1.4 m s^{-1}; c) Cooper-Haines, (1996) data assimilation twin of the weak Gulf Stream; and d) MODAS synthetic temperature and salinity profile data assimilation twin of the stronger Gulf Stream

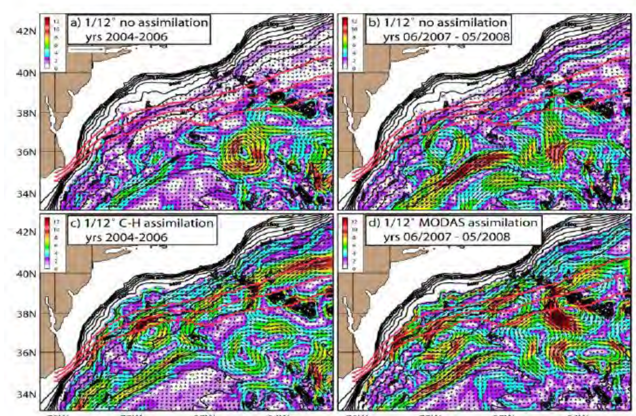

Figure 6. Mean depth-averaged velocities in layers 27 to 29 (~3,500–4,500 m) four 1/12° global HYCOM simulations: a) inter-annually forced weak Gulf Stream with separation velocity of 1.1 m s^{-1}; b) inter-annually forced stronger Gulf Stream with separation velocity of 1.4 m s^{-1}; c) Cooper-Haines, (1996) data assimilation twin of the weak Gulf Stream, and d) MODAS synthetic temperature and salinity profile data assimilation twin of the stronger Gulf Stream

The inter-annual simulation, without the QuikSCAT correction, generates a weak Gulf Stream. The separation velocity is only 1.1 m s^{-1} and the mean core speed decreases rapidly to the east with a speed less than 0.4 m s^{-1} near 72°W. The weak Gulf Stream is associated with weak mean abyssal currents. The key southward abyssal current at 72°W is weak with a speed less than 4 cm s^{-1} and displaced to the south, and the key current at 68.5°W is absent along with the associated deep cyclonic gyres as seen in the observations. The strongest abyssal flows are an anti-cyclonic gyre at (36°N, 66°W), which steers the Gulf Stream slightly northward. Near Cape Hatteras, the mean Gulf Stream shows two pathways, one path clinging to the continental slope while another pathway turns almost due-east. After separation, the mean pathway lies southward of the mean IR pathway. The MOC is weak and shallow with a transport less than 11 Sv. Evidence for weak baroclinic instability can be found in: 1) the large area of high-SSH variability west of 70°W, 2) a weak southern recirculation gyre west of 70°W, and 3) the eddy driven mean abyssal gyre centered directly beneath the surface gyre.

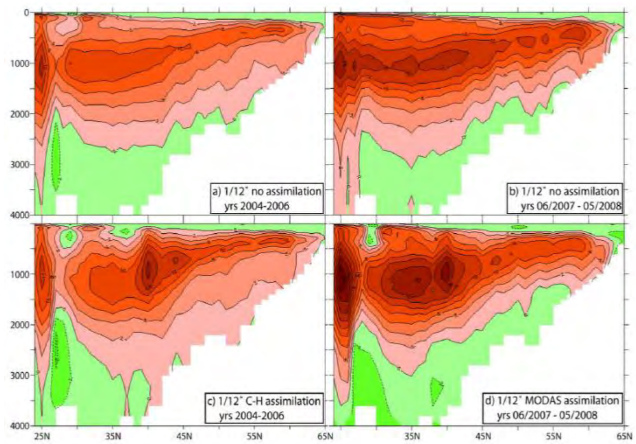

Figure 7. Meridional overturning circulation stream function for four 1/12° global HYCOM simulations: a) inter-annually forced weak Gulf Stream with separation velocity of 1.1 m s^{-1}; b) inter-annually forced stronger Gulf Stream with separation velocity of 1.4 m s^{-1}; c) Cooper-Haines, (1996) data assimilation twin of the weak Gulf Stream; and d) MODAS synthetic temperature and salinity profile data assimilation twin of the stronger Gulf Stream

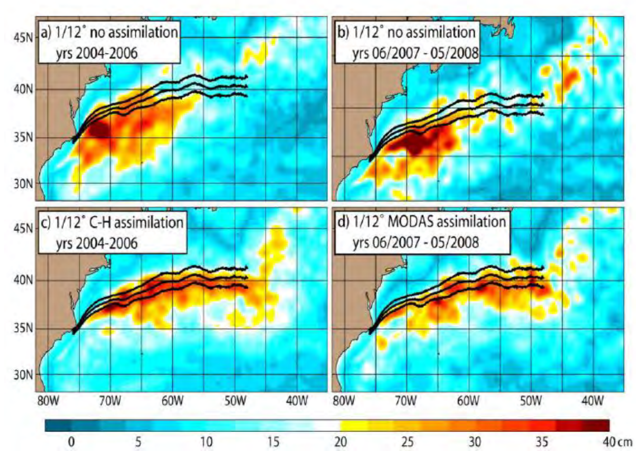

Figure 8. Standard deviation of the sea surface height for four 1/12° global HYCOM simulations: a) inter-annually forced weak Gulf Stream with separation velocity of 1.1 m s$-^{-1}$; b) inter-annually forced stronger Gulf Stream with separation velocity of 1.4 m s^{-1}; c) Cooper-Haines, (1996) data assimilation twin of the weak Gulf Stream; and d) MODAS synthetic temperature and salinity profile data assimilation twin of the stronger Gulf Stream

The hindcast with weaker, uncorrected winds assimilates SSH by adjusting the layer thickness as proposed by Cooper and Haines, (1996). In the hind cast, the mean Gulf Stream follows the observed path from the coast out to 68°W. East of 68°W, the flow diverts southward of the observed path, turning sharply northward, and splitting as the Stream crosses the New England Seamount Chain (NESC) at 64°W. The SSH variability reproduces all of the features found in the observed altimetric SSH variability. The separation velocity is relatively weak at only 1.1 m s^{-1}. The assimilative Gulf Stream is much stronger to the east with mean speeds of 0.8 m s^{-1} at 70°W and 0.6 m s^{-1} at 65°W. A surprising result is the strong abyssal circulation in the assimilative simulation. The key abyssal currents at 72°W and 68.5°W are present with strengths of 10 cm s^{-1} and 8 cm s^{-1}, respectively. The southward flow at 72°W is associated with a cyclonic gyre. The MOC is stronger, with transport greater than 18 Sv, and much deeper than in the non-assimilative simulations. Despite a weaker Gulf Stream at Cape Hatteras, data assimilation generates a vigorous eddy field which drives a strong abyssal circulation.

The second hindcast uses stronger QuikSCAT-corrected winds and assimilation is performed through the Navy Coupled Ocean Data Assimilation System (NCODA) with the SSHA extended into the ocean interior using synthetic profiles of temperature and salinity from MODAS. The mean Gulf Stream follows the observed path extremely well to the east past the NESC to 62°W. The separation velocity is weak, only 1.0 m s^{-1}. However, core speed is a maximum of 1.2 m s^{-1} at 72°W, and exceeds 0.65 m s^{-1}at 65°W. The SSH variability reproduces the observed altimetric SSH variability .The eddy driven abyssal circulation is strong, with the key southward abyssal currents exceeding 10 cm s^{-1}. Each of the key currents is associated with a strong cyclonic-gyre. The MOC is the strongest, exceeding 20 Sv, and deepest of any of the four simulations. Assimilating the MODAS synthetic profiles appears to generate the most realistic Gulf Stream system, with strong eddies along the entire path driving a strong abyssal circulation. Regardless of the assimilation technique, the pathway of the Gulf Stream is improved with stronger penetration to the east, the MOC is deepened and strengthened by 5–6 Sv, the eddy driven abyssal circulation is strengthened, and the key abyssal steering currents at 72°W and 68.5°W reproduced.

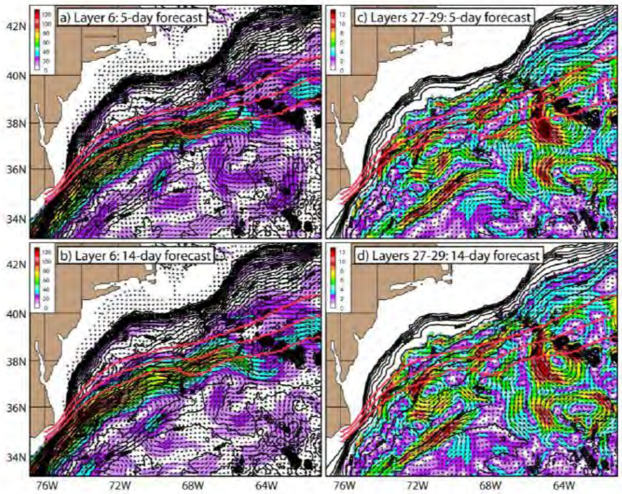

Figure 9. The mean velocities for the forecasts starting from the state estimates of the MODAS data assimilation with the layer 6 (~25 m) velocities for the a) 5-day forecast and the b) 14-day forecast and the layer 27 to 29 (~3,500–4,500 m depth) velocities for the c) 5-day forecast and the d) 14-day forecast

5. Impact of Data Assimilation on Gulf Stream Forecasts

In the hindcasts, we found that assimilating SSH anomalies improves the mean characteristics of the Gulf Stream in terms of mean pathway and extension to the east, but the Gulf Stream is very weak, only 1.1 m s^{-1}, which is much weaker than the observed speed at separation. A series of forecasts are presented to show the performance of data assimilation on the Gulf Stream. The mean velocities in layer 6 (~25m) and layers 27–29 (~3,500 m to 4,500m) from 48 forecasts are shown to the left. The 5-day forecast has appreciable skill with a median SSH anomaly correlation of 0.8, but the 14-day forecast has little skill. In the forecasts, we find significant changes in the upper layer flow, but only modest changes in the abyssal circulation. The 5-day forecast still tracks the mean IR path west of the NESC (64°W), but the core speeds have decreased by approximately 0.1 m s^{-1} along the entire Stream. The core speeds in the 14-day forecast have decreased substantially with the speed at 72°W dropping below 0.8 m s^{-1}. The path of the Gulf Stream is deflected southward around 68.5°W, presumably steered southward by the strong southward abyssal current at 68.5°W. The MOC (not shown) for the 14-day forecast is slightly weaker and shallower than either the 5-day forecast or analyses. The Gulf Stream in the forecasts is still inertial, with the variability driven by the instability of the flow. However, the dynamics of the model are insufficient to maintain a strong flow eastward to the NESC and the forecast Gulf Stream weakens over the 14-day period. The abyssal circulation appears to have a longer time-scale showing little change in the mean over the 14-day forecast period. Thus, the steering by the abyssal currents helps to maintain a reasonable pathway, but the dynamics cannot maintain the strength of the Gulf Stream.

6. Conclusions

Data assimilation provides a surprising change in the modeled behavior of the Gulf Stream. The non-assimilative simulations fail to generate a strong abyssal circulation and have a weak overturning circulation. The Gulf Stream path is poorly simulated without the steering by the abyssal circulation. A resolution increase from 1/12° to 1/25° increases the strength of the abyssal circulation, but fails to generate strong flows at the key abyssal locations. Data assimilation forces the Gulf Stream to reproduce the pathway and sea level variability seen in satellite altimetry. The mean currents of the Gulf Stream near the surface are weaker than the non-assimilative simulations, but extend much farther eastward with greater velocities. The eddies and meanders forced by the data assimilation drive a robust abyssal circulation reproducing the key currents identified by Hurlburt and Hogan, (2008), and observed in the deep current meter records. The mean abyssal circulation is persistent over at least 14-days, which helps improve the pathway of the mean Gulf Stream in the forecasts compared to the non-assimilative simulations. However, the weaker Gulf Stream fails to generate realistic meanders and the skill in predicting the instantaneous pathway decreases rapidly, while the mean pathway remains realistic.

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References

Barron, C.N., L.F. Smedstad, J.M. Dastugue, and O.M. Smedstad, "Evaluation of ocean models using observed and simulated drifter trajectories: Impact of sea surface height on synthetic profiles for data assimilation." *Journal of Geophysical Research*, 112, C07019, doi: 10.1029/2006JC002982, 2007.

Cooper, M. and K.A. Haines, "Altimetric assimilation with water property conservation." *Journal of Geophysical Research*, 24, pp.1059–1077, 1996.

Hurlburt, H.E. and P.J. Hogan, "The Gulf Stream pathway and the impacts of the eddy-driven abyssal circulation and the Deep

Western Boundary Current." *Dynamics of Atmospheres and Oceans*, 45, pp. 71–101, 2008.

Hurlburt, H.E., E.J. Metzger, J.G. Richman, E.P. Chassignet, Y. Drillet, M.W. Hecht, O. Le Galloudec, .F.Shriver, X. Xu, and L. Zamudio, "Dynamical evaluation of ocean models using the Gulf Stream as an example," *Operational Oceanography in the 21st Century*, G.B, Brassington and A. Schiller, eds., Springer-Verlag, New York, 2010 (in press).

Kara, A.B., A.J. Wallcraft, P. J., Martin, and R.L. Pauley, "Optimizing surface winds using QuikSCAT measurements in the Mediterranean Sea during 2000–2006." *Journal of Marine Systems*, 78, pp.119–131, 2009.